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Comparative environmental performance of lignocellulosic ethanol from different feedstocks

Sara González-García *, M. Teresa Moreira, Gumersindo Feijoo

Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain

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ABSTRACT

A renewable biofuel economy is projected as a pathway to decrease dependence on fossil fuels as well as to reduce greenhouse gases (GHG) emissions. Ethanol produced on large-scale from lignocellulosic raw materials is considered the most potential next generation automotive fuel. In this paper, a Life Cycle Assessment model was developed to evaluate the environmental implications of the production of ethanol from five lignocellulosic materials: alfalfa stems, poplar, Ethiopian mustard, flax shives and hemp hurds and its use in passenger cars. Two ethanol-based fuel applications, E10 (a mixture of 10% ethanol and 90% gasoline by volume) and E85 (85% ethanol and 15% gasoline by volume) were assessed and the results were compared to those of conventional gasoline (CG) in an equivalent car.

The environmental performance was assessed in terms of fossil fuels requirements, global warming, photochemical oxidant formation, acidification and eutrophication by means of the Life Cycle Assessment (LCA) methodology in order to identify the best environmental friendly lignocellulosic source. The results show that, compared to CG, life cycle greenhouse gases emissions are lower for etanol blends, specifically up to 145% lower for E85-fueled car derived from Ethiopian mustard. This crop is also the best option in terms of eutrophying emissions regardless the ratio of ethanol in the blend. In the remaining impact categories, other feedstocks are considered beneficial, that is, poplar in the case of photochemical oxidants formation and flax shives for acidification. Concerning fossil fuels requirements, decreases up to 10% and 63% for E10 and E85 derived from hemp hurds and Ethiopian mustard, respectively, were obtained.

According to the results, the study clearly demonstrates the importance of using low intensive energy and high biomass yield crops. LCA procedure helps to identify the key areas in the ethanol production life cycle where the researchers and technicians need to work to improve the environmental performance. Technological development could help in lowering both the environmental impact and the prices of the ethanol fuels.

Contents

* Corresponding author. Tel.: +34 981563100x16776; fax: +34 981547168.
E-mail address: sara.gonzalez@usc.es (S. González-García).

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1. Introduction

The steady increase in energy consumption and current dependence on crude oil to meet energy demands have motivated more and more support for the use of renewable energies. Hence, renewable energy is seen as a long-term solution to establish reliable sources of energy supply [1]. Transport sector is almost entirely dependent on fossil fuels. For this reason, the use of biofuels for transport is becoming of increasing importance for a large number of reasons, such as environmental concerns (climate change or depletion of fossil fuels) and reducing reliance on imports.

Ethanol has attracted special attention due to its potential use as an automotive fuel and its environmental, energy and socioeconomic advantages relative to fossil fuel consumption and greenhouse gases (GHG) emissions reduction [2–5]. Typically, ethanol has been produced from starch and sugar crops such as cassava, wheat, barley, corn grain or sugarcane [6–9]. Alternative biomass raw materials can be used as 2nd generation ethanol [6,10–16]. The 2nd generation term means that, contrary to 1st generation biofuels (e.g. bioethanol from sugar or starch plants or biodiesel from rapeseed or palm oil), non-food raw materials are used. These raw materials include mainly lignocellulosic raw materials such as energy crops (e.g. switchgrass), straw, wood and various agricultural and wood processing waste products.

Lignocellulosic feedstocks are the largest sources of hexose (C_6) and pentose (C_5) sugars with a potential for the production of biofuels, chemicals and other economic by-products [17]. However, these materials are more complex substrates than starch materials. They are composed of carbohydrate polymers (cellulose and hemicellulose) and lignin and, unlike starch carbohydrates which are easily depolymerized into fermentable sugars, carbohydrates fractions in lignocelluloses are not readily available for hydrolysis and a pretreatment stage is necessary [18]. Therefore, highly efficient conversion of carbohydrates to fermentable sugars is essential to commercially competitive biological processes for making cellulosic ethanol [4]. Several studies were performed on the environmental impact of ethanol, focusing mainly on two main aims related to the use of biofuels: (i) reduction of fossil fuel extraction and, (ii) reduction of GHG [7,10,15,19–22]. According to these studies, the production and use of cellulosic ethanol have the potential to result in significant abatement of GHG emissions since the carbon released as CO_2 from combustion and production of the fuel would be incorporated into the re-growth of the plant. Moreover, reduction of up to 50% of fossil fuel consumption could be achieved in comparison with gasoline [15].

In this context, Life Cycle Assessment (LCA) methodology has proven to be a helpful tool to evaluate the environmental impacts of product and processes under a holistic approach [23]. Several available LCA studies have identified the environmental performance of the ethanol production from different feedstocks and its use in automobiles [14,15,24–33]. Numerous studies have been published on production of ethanol from grains (corn and wheat) and its environmental performance in passenger cars [24,25]. Sugar industrial by-products, e.g. cane molasses [26], sugarcane bagasse [15] and sugar crops such as sugar beet [27] are examples of common feedstocks in tropical countries. Lignocellulosic materials such as corn stover, switchgrass, salix, spruce were also extensively assessed as raw materials to produce ethanol [14,15,28,29]. From all these studies, it can be concluded that large-scale use of lignocellulosic ethanol would require more sustainable and cost-effective practices in agriculture as ethanol production is highly dependent on feedstock cost as well as the development of advanced technologies in ethanol biorefinery [30]. Other potential lignocellulosic feedstocks analysed in the formulation of ethanol-based fuels are flax shives [21], hemp hurds [31], poplar [32], Ethiopian mustard [22] and alfalfa stems [33]. The results from all these studies concluded that there is a potential reduction in GHG emissions and fossil fuel dependence when using this type of ethanol although contributions to some impact categories (e.g. acidification, eutrophication or ecotoxicity) would be increased in comparison with gasoline.

This paper aims to compare and validate the production and use as transportation fuel ("well-to-wheel" perspective) of ethanol in a middle size passenger car produced from different potential lignocellulosic feedstocks (alfalfa stems, flax shives, hemp hurds, poplar and Ethiopian mustard) using the LCA approach in terms of fossil fuels requirement and four impact categories (global warming, photochemical oxidant formation, acidification and eutrophication) using the LCA approach. The uses of different methodologies as well as different system boundaries make difficult the comparison of the results. For this reason, to permit a direct comparison of fuel ethanol from different lignocelluloses, the same conversion technology was used to convert biomass to ethanol (acid hydrolysis followed by simultaneous saccharification and fermentation and distillation) and the same system boundaries were defined.

Especially, the analysis compares the environmental performance of (i) ethanol in a 10% blend with gasoline (E10) and (ii) ethanol in a 85% blend with gasoline (E85) with conventional gasoline (CG). The assessment encompasses cultivation of the crop, ethanol production stage, ethanol blend production and blend use. In some of these lignocellulosic feedstocks, the agricultural process yields more than one product (e.g. fibre and lindseed in the flax crop) and it was necessary to allocate the environmental burdens from feedstock cultivation between all the agricultural co-products. Therefore, mass allocation was assumed as main line in order to have the same allocation procedure in all agricultural systems. The environmental performance shown in this paper reflects the advantages and disadvantages of using lignocellulosic ethanol blends instead of conventional gasoline, the influence of the allocation approach as well as the nature of feedstock and agricultural production.

The results provide an overview on the energy efficiency and environmental performance of using fuel ethanol derived from different feedstocks as well as the advantages and disadvantages of using lignocellulosic ethanol blends in comparison with conventional gasoline, the influence of the allocation approach and the nature of feedstock and, agricultural production.

2. Materials and methods

2.1. Methodology

Life Cycle Assessment (LCA) is defined as a methodology for the comprehensive evaluation of the impact that a product has on the environment throughout its life cycle (from extraction of raw materials to manufacture, use, recycling and disposal) [34]. The present study concerns the general comparison of technologies for the car driving function, without specific local circumstances playing a role.

The life cycle models for five potential feedstocks (alfalfa stems, Ethiopian mustard, poplar, flax shives and hemp hurds) were developed to quantify the inputs and outputs of the process, including energy, chemicals and environmental emissions. An identical ethanol production technology, system boundaries and allocation procedure were assumed in order to make the systems comparable.

2.2. Cellulosic ethanol fuel and functional unit

The goal of this study was to compare the environmental performance of internal combustion engine automobiles fuelled with gasoline and lignocellulosic ethanol derived from different raw materials in order to identify the more environmental friendly feedstock.

As a vehicle fuel, ethanol is mainly used in two ways. The first one is blended with gasoline, typically 5–20% by volume, for use in conventional vehicles with no engine modifications. The second is to use ethanol (85–100%), in vehicles with specifically modified engines. In this study, ethanol is assumed to be used as a mixture of 10% ethanol and 90% gasoline by volume (from now, E10) and a mixture of 85% ethanol and 15% gasoline by volume (from now, E85) on a middle size flexi fuel vehicle with no engine modifications (from now, FFV). Therefore, the different fuel formulations considered for comparison were gasoline (CG), E10 and E85, in amounts required to deliver the same amount of energy "to the wheels".

The function of this study is to drive a FFV; therefore, the functional unit chosen is 1 km distance driven by a FFV. Under these conditions, the amount of fuel required for travelling 1 km is calculated to be 66 g for CG, 69 g for E10 and 92 g for E85. The average fuel economy considered in the FFV under study running with CG, E10 and E85 was 10.91, 10.51 and 8.29 km/L, respectively [25,35].

2.3. Raw materials

The raw materials considered in this study: alfalfa stems, Ethiopian mustard, poplar, flax shives and hemp hurds, are abundant renewable cellulosic materials, which can be potentially converted into ethanol (and other high value products) and present a composition close to that of the wood species (Table 1) [21,22,31–33].

2.4. System boundaries

In order to get comparable and consistent data, it is crucial to have a clear definition of the system boundaries. An overview of the assumed ethanol process, which was the same for all five raw materials studied, is shown in Fig. 1. The model used in the study is an updated and somewhat modified version of the model described by Aden et al. [18]. The proposed ethanol plant is assumed to be located in Spain, with a processing capacity of 98,958 kg of raw material per hour, operative during 8160 h per year. All relevant processes were included within the boundary of the fuel systems, as shown in Fig. 1 and the systems were divided in four main subsystems: feedstock cultivation (S1), ethanol biorefinery (S2), ethanol blends production (S3) and final use (S4), which are briefly described below. Furthermore, both production of capital goods and waste management were also included within the system boundaries. However, production and disposal of the car were left outside of the system boundaries.

2.4.1. Feedstock cultivation subsystem

The raw materials for ethanol production may either come from agricultural and forest wood wastes or, if the product demand is high enough, from cultivated feedstock. This subsystem includes not only all agricultural field operations for each feedstock (e.g. field management, pesticide, herbicides and fertilizers application, sowing and harvesting), but also operations related to the post-preparation of the product, if necessary (such as retting, drying, scutching, raking and baling). The mentioned field and post-preparation operations correspond to Spanish plantations. The subsystem boundaries included the production of process materials such as fertilizers, pesticides and fuel for operating agricultural machinery production as well as their transportation to the farm gate.

2.4.2. Ethanol biorefinery subsystem (S2)

The ethanol production materials and energy balances as well as ethanol yield were based on the ethanol conversion technology reported by the National Renewable Energy Laboratory [18] from corn stover, assuming that ethanol production efficiency is equivalent for other crops. In this case, feedstock composition was adapted to each biomass composition (Table 1).

In the ethanol conversion process, cellulose and hemicellulose are used for ethanol production. The lignin fraction of the biomass has high heating value and can be used as fuel (as well as syrup,

Table 1
Assumed composition (dry basis) of feedstocks delivered to the refinery gate.

Component	Compositions (weight fraction)				
	Alfalfa stems	Ethiopian mustard	Poplar	Flax shives	Hemp hurds
Cellulose	0.275	0.327	0.432	0.477	0.374
Hemicellulose	0.230	0.219	0.266	0.170	0.276
Xylan	0.086	0.180	0.216	0.130	0.211
Arabinan	0.018	0.012	0.033	0.018	0.029
Other sugar polymers	0.126	0.027	0.017	0.022	0.036
Lignin	0.158	0.187	0.213	0.266	0.180
Acetate	0.018	0.013	0.013	0.030	0.029
Ash	0.081	0.052	0.015	0.010	0.052
Others	0.238	0.196	0.061	0.047	0.089
Total	1.00	1.00	1.00	1.00	1.00

Others consist mainly of extractives, and were modeled as either volatile or non-volatile compounds in order to close the mass balances as accurately as possible.

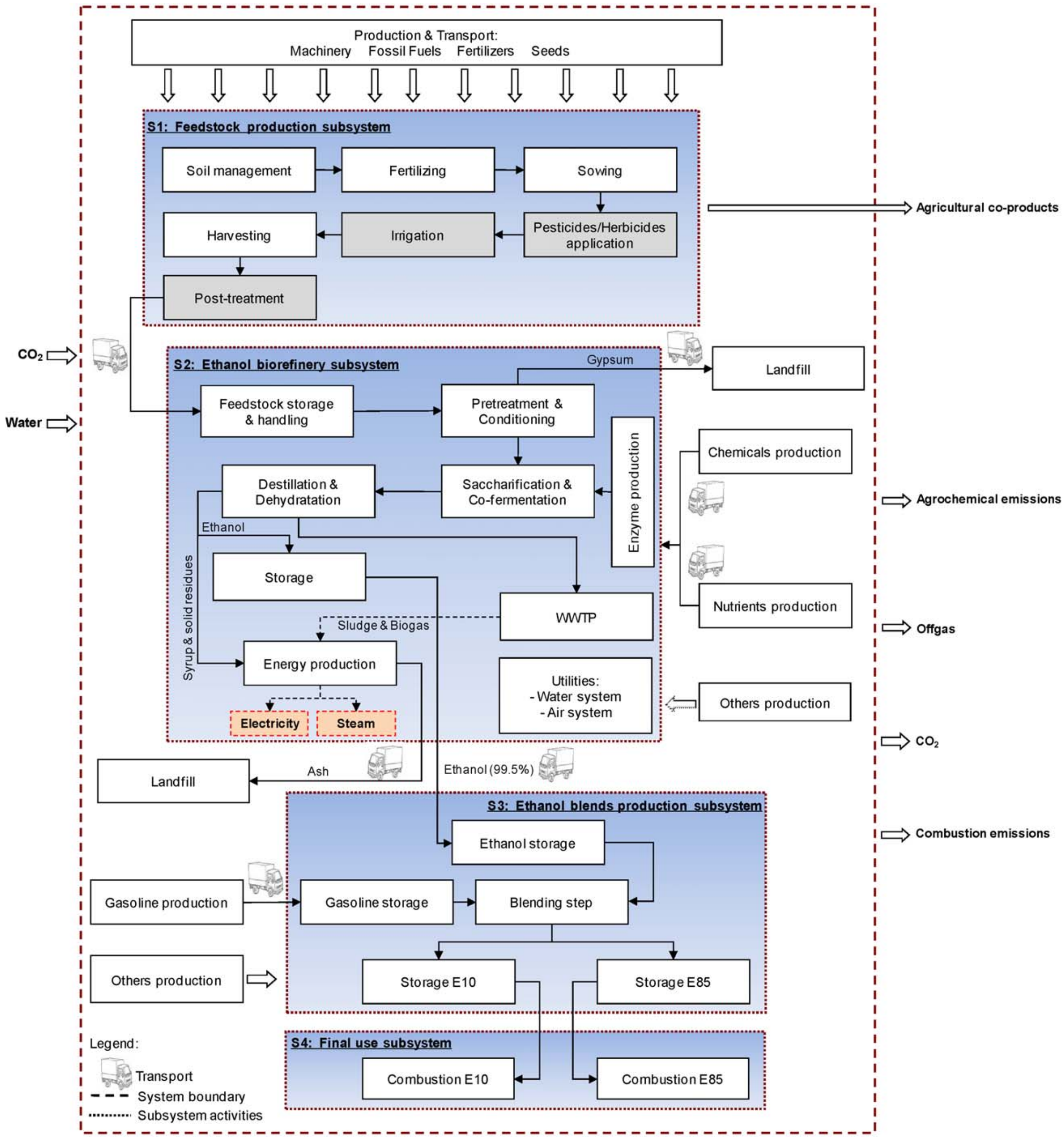

Fig. 1. System boundaries of lignocellulosic based ethanol E10 and E85 fuels life cycle. White boxes are common to all crops; gray boxes only take place in some crops.

sludge and anaerobic biogas produced in the wastewater treatment plant, WWTP) in a lignin combustor in order to produce the energy requirements (heat and electricity) for the plant (self-sufficient). An overview of the ethanol process assumed is shown in Fig. 1. This subsystem was divided in nine processes: (i) feedstock handling and storage; (ii) pretreatment and conditioning (where biomass is treated with dilute sulphuric acid and steam to liberate the hemicellulose sugars and other compounds); (iii) saccharification (or enzymatic hydrolysis) and co-fermentation; (iv) distillation and dehydration (including evaporation and solid–liquid separation) to purify and concentrate ethanol up to 99.5%; (v) storage of ethanol; (vi) wastewater treatment plant (WWTP) where the bottoms of the distillation process and evaporator condensates are treated. The water treated is recycled to the refinery; (vii) energy production (electricity and process heat) from solids from distillation, syrup and biogas, (viii) enzyme production, where all enzymes required in the process are produced and finally (iv) ancillary utilities, which include the production of cooling, sterile and process water and compressed air. Gypsum from the solid–liquid separation and ashes from the energy production are sent to landfill.

2.4.3. Ethanol blends production (S3)

The distribution of ethanol from the biorefinery to a gasoline station was assumed to be carried out by 32 t diesel lorries over an average distance of 20 km. The production of the gasoline as well as its transport to the gasoline station, the mixture of gasoline and ethanol to produce the blends under study (E10 and E85) and their

regional storage were also included within the subsystem boundaries. When pure gasoline is used as fuel, its delivery to a regional storage was also considered in this subsystem.

2.4.4. Final use (S4)

Emissions derived from fuel use in a FFV were calculated according to the economy fuels and the functional unit selected. Manufacture, maintenance and disposal of the FFV were excluded from the subsystem boundaries.

2.5. Inventory analysis

The most arduous step in the implementation of LCA studies is the collection of inventory data to build the life cycle inventory (LCI). Moreover, high quality data is essential for a reliable evaluation. We handled a large amount of data, including agrochemicals production, diffuse emissions from fertilizers, pesticides and herbicides application, transport systems and ethanol production. The procedure for the LCI of the system under study is summarized in Table 2. As this table shows, data for the study were collected from different sources and by different methods, including field data, research reports and literature, to ensure the reliability of the study. Fig. 2 shows the ethanol production per every biomass source as well as the amount of dry biomass processed in terms of kg per h (in all case studies the input of green biomass into the biorefinery is 98,958 kg/h). Table 3 shows a short description of agricultural practices related to each feedstock under study in this paper.

2.6. Allocation approach

Allocation defined as the partitioning of input or output flows of a unit process to the product under study, is one of the most crucial issues in the LCA. In some agricultural crops, allocation was necessary since they yield more than one product (e.g. alfalfa, flax and hemp). Each allocation method (mass, economic or energy)

Table 2
Data sources for the life cycle inventory of lignocellulosic ethanol production.

Subsystem	Data required	Data sources
S1	Fuel use	Research report [36]
	Fertilizer use	
	Labour use	Literature [21,22,31–33]
	Consumable materials transport (mode, capacity and distance)	Research reports [37]
	Diffuse emissions	Research reports [38–41]
	Feedstock transport (mode, capacity and distance)	Research report [37]
S2	Production capacity	Research reports [18,37,42–45]
	Chemicals use	
	Nutrient use	Literature [21,22,31–33]
	Enzyme production	
	Landfill operation	
	Energy requirements	
	Industrial equipment use	
	Wastewater treatment plant	
	Consumable materials transport (mode, capacity and distance)	Research report [37]
S3	Gasoline production and transport (mode, capacity and distance)	Research reports [29,37,43]
	Ethanol transport (mode, capacity and distance)	
	Ethanol, gasoline and blends storage	
S4	Fuel use	Research reports [46,47]
	Emission data of car driving	

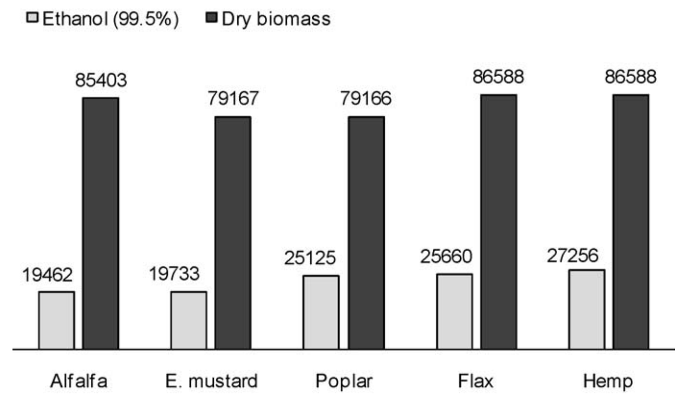

Fig. 2. Ethanol production and dry biomass processed expressed in kg/h. Total biomass processed = 98,958 kg/h.

has its advantages and disadvantages and the choice of allocation procedure depends on the goal of study. Alfalfa crop produces leaves and stems in the same proportion. Flax crop produces fibres (the driving force) for specialty paper pulp production, linseeds and shives. Hemp crop produces fibres, hurds and dust. Mass allocation was assumed as the base line in all case studies in order to permit a fair comparison. The partitioning ratios based on biomass production are given in Table 4. As regards ethanol production, allocation was avoided because all electricity produced from wastes in the biorefinery is consumed in the ethanol production process and there is no surplus of electricity. In addition, solid residues generated in the biorefinery (e.g. gypsum and ash) are sent to landfill and were thus regarded as wastes. Thus, all the environmental burdens of the S2 were allocated to the ethanol (the main product).

3. Results

Life Cycle Impact Assessment was conducted using characterization factors from CML methodology [48]. The following parameters were considered in the analysis: global warming (GW), photochemical oxidants formation (PO), acidification (AC), eutrophication (EP) and fossil fuel extraction (FF). Special attention was paid to the GHG emissions and fossil fuel use to satisfy the two challenges for the EU in terms of transport fuels [49], viz. (i) reducing GHG emissions and (ii) protecting energy supply.

3.1. Global warming (GW)

Fig. 3 shows the contributions in terms of equivalent CO_2 emissions per functional unit taking into account the blend and lignocellulosic raw material. According to our results, GHG emissions slightly decrease when shifting from CG to E10 regardless the feedstock. The use of E85 seems to be more advantageous than E10 in terms of GHG emissions. If the contributions to GW are analysed in detail, emissions are mainly due to three global warming gases: CO_2, N_2O and CH_4 (Table 5). CH_4 and N_2O emissions increase when changing from CG to ethanol blends regardless the percentage of ethanol in the blend. These emissions are mainly derived from the agricultural step (specifically, production and application of N-fertilizer and use of agricultural machinery). However, it should be necessary to mention the positive effect of the CO_2 sequestered during the biomass growth which counteracts part of GHG emissions. Specifically in the case of ethanol from Ethiopian mustard, the results show that when E85 is used as fuel, the most important contribution to equivalent CO_2 emissions is the CO_2 taken up during the biomass growth which balances CO_2 derived from

Table 3
Mass balance of the feedstocks culture (ha).

	Alfalfa	E. mustard	Poplar	Flax	Hemp
Fertilizers specification	36.2 kg N 103.2 kg K_2O 101.4 kg P_2O_5	250 kg ammonium nitrate 350 kg 8N/24P/8K	500 kg N (33.5%) 1200 kg 9N/18P/27K	30.1 kg N 41.8 kg K_2O 41.8 kg P_2O_5	85 kg N 125 kg K_2O 65 kg P_2O_5
Phytosanitaris specification	24.2 kg borax	2 L glyphoste	4 L glyphosate 1 L metil-pirimidos 0.5 L propineb (70%)	0.47 kg MCPA (40%)	–
Diesel use	299.4 kg	66.2 kg	259 kg	60.1 kg	74.9 kg
Biomass (o.d.)	11.9 t/year	4.7 t/year	13.5 t/year	5.4 t/year	2.6 t/year
Years	4.5	1	15	1	1
NH_3	6.0	1.9	10	1.6	3.1
N_2O	6.6	1	3	1.2	4.8
NO_3^-	276	–	–	13	342
NO_x	–	0.2	0.3	0.1	0.5

o.d.: oven dry.

agricultural machinery use, ethanol conversion plant and blend use (Fig. 3). Reductions up to 88% of total GHG emissions can be achieved with other lignocellulosic sources such as alfalfa stems. On the contrary, when E10 is used, the lowest amount of ethanol in the blend supposes a lower contribution from the CO_2 taken up, which cannot make up for CO_2 emissions from blend use and fossil fuel production. Regardless the biomass source, the CO_2 equivalent emissions are lower than when the same distance is driven with CG (Table 5).

3.2. Photochemical oxidants formation (PO)

Fig. 4 shows the contributions in terms of equivalent C_2H_4 emissions per functional unit taking into account the blend and lignocellulosic raw material. The results show the increase of contributions to PO when shifting from CG to ethanol blends. This impact category is affected considerably by agricultural activities due to emission of photo-oxidants derived from biomass cultivation step such as SO_2 emissions from P-based fertilizer manufacture and, CO and NMVOC from diesel combustion in agricultural machinery [50,51]. There are also diffuse emissions of acetic acid and ethanol from the ethanol conversion related steps (enzyme and energy production, distillation and feedstock handling) which contribute to PO. Therefore, E10 shows better environmental performance than E85 in terms of PO regardless the feedstock. The higher proportion of ethanol in the blend is the main responsible of PO contributions.

3.3. Acidification (AC)

Fig. 5 shows the comparative environmental performance in terms of equivalent SO_2 emissions per functional unit. According to these results, increasing the ratio of ethanol in the blend produces more acidifying emissions (E10 is more environmental friendly fuel). Once again, upstream activities are the main contributors, especially agricultural activities, mainly due to the production of agrochemicals and the use of agricultural machinery (combustion emissions from diesel). Therefore, more SO_2 and NO_x are emitted to the atmosphere. The diffuse emissions derived from the application of fertilizers are another important hot spot in terms of AC mainly due to N-based emissions.

3.4. Eutrophication (EP)

In the EP, the results are similar to the results obtained in AC and Fig. 6 shows the comparative environmental profile in terms of equivalent PO_4^{3-} emissions per functional unit. According to the results, increasing the ratio of ethanol in the blends produces more eutrophying emissions. Moreover, activities related to feedstocks cultivation were identified as the main source of eutrophying emissions. This high contribution is mainly due to nitrogen (NH_3 and NO_x) and phosphorous related emissions, combustion emissions from agricultural machinery and tractor and, fertilizer production.

3.5. Fossil fuels extraction (FF)

Fig. 7 shows the results in terms of fossil fuel extraction (in kg coal eq per km) and according to the results, shifting from CG to ethanol blends results in a reduction of non-renewable fuel requirements. On the one hand, shifting from CG to ethanol blends increases the consumption of liquid fuel by agricultural machinery (usually diesel) and on the other hand, less gasoline is necessary to propel the car. Therefore, determining the net amount of equivalent coal throughout the life cycle, as much higher are the reductions of FF for ethanol blends as much higher is the ratio of ethanol in the blend. Reductions up to 10% and 63% can be

Table 4
Partitioning fraction for mass allocation.

	Potential feedstock	Leaves	Fibres	Lindseed	Dust
Alfalfa	50%	50%	–	–	–
E. mustard	100%	–	–	–	–
Poplar	100%	–	–	–	–
Flax	67.5%	–	25%	7.5%	–
Hemp	5%	–	33.3%	–	16.7%

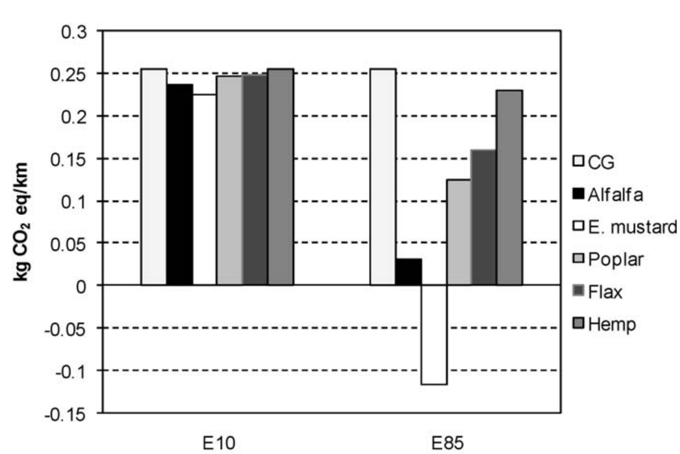

Fig. 3. Global warming comparison between ethanol blends and feedstocks.

Table 5
Distribution of GHG emissions per fuel and feedstock under study.

	CG	Alfalfa	E. mustard	Poplar	Flax	Hemp
E10						
CO_2 (kg CO_2 eq/km)	0.2510	0.2320	0.2180	0.2330	0.2410	0.2370
N_2O (kg CO_2 eq/km)	0.0002	0.0004	0.0024	0.0084	0.0032	0.0134
CH_4 (kg CO_2 eq/km)	0.0037	0.0036	0.0034	0.0034	0.0038	0.0038
GHG (kg CO_2 eq/km)	0.2550	0.2360	0.2240	0.2450	0.2480	0.2540
E85						
CO_2 (kg CO_2 eq/km)	0.2510	0.0136	-0.1450	0.0289	0.1200	0.0794
N_2O (kg CO_2 eq/km)	0.0002	0.0135	0.0256	0.0937	0.0323	0.1410
CH_4 (kg CO_2 eq/km)	0.0037	0.0042	0.0020	0.0021	0.0069	0.0070
GHG (kg CO_2 eq/km)	0.2550	0.0310	-0.1170	0.1250	0.1590	0.2270

achieved in E10 (considering hemp hurds based ethanol) and E85 (considering Ethiopian mustard based ethanol), respectively.

4. Discussion

The current dependence on oil for energy and production of numerous chemicals and products together with climate change concern has put tremendous focus on finding alternative renewable sources for the production of fuels and chemicals. Lignocellulosic raw materials are composed of up to 75% carbohydrates, and in the near future it will become an essential source for fermentable carbohydrates. For this reason, there are a few obstacles and constraints that need to be overcome if 2nd generation ethanol is to be regarded as a sustainable and cost-effective source of energy. Nowadays, biofuels are commercially uncompetitive with fossil fuels (gasoline and diesel) in Europe because technology is under development. In spite of several advances reported on bioethanol production from lignocellulosic feedstocks, the price of cellulosic ethanol remains around at $0.70 per litre due to feedstock, hydrolysis and ethanol recovery costs, among others [5]. Even though lignocellulosic biomass is abundant and inexpensive, not all cellulose biomass is suitable and can be used as feedstock due to the restrictions of the present technology to hydrolyze biomass efficiently in terms of cost and energy consumption [52]. However, more and more pilot-scale facilities for pretreatment are being constructed, facilitating much better evaluation of the technologies, their constraint and opportunities [53].

A limited number of bacteria, yeast and fungi can convert hemicellulose or its monomers (xylose, arabinose, mannose and galactose) into ethanol with satisfactory yield and productivity. The yield of ethanol in all these feedstocks ranges from 0.23 to 0.32 t ethanol/t of oven dried feedstock considering the same hydrolysis process and microorganisms (Fig. 2). These yields fit in with other previous published studies [5,18,20] for different lignocellulosic raw materials, microorganisms and, hydrolysis and fermentation conditions.

Several LCA studies of different ethanol-gasoline blends from lignocellulosic feedstocks [54,55] and sugar crops [26,27,50,51] were revised to show that the choices of system boundaries, the definition of functional unit and allocation procedures play an important role in the LCA of ethanol blends. In this paper, the aim

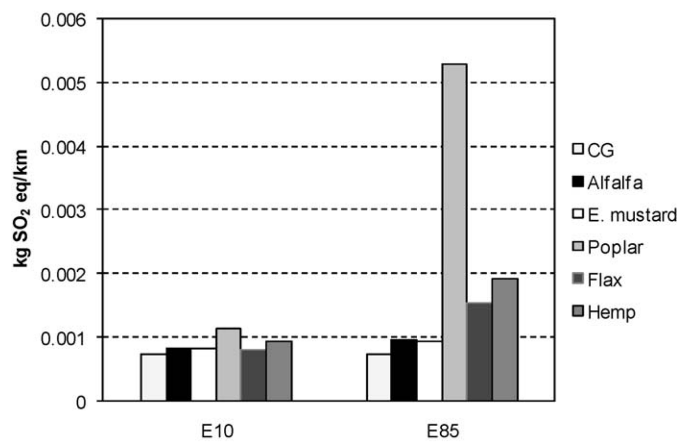

Fig. 5. Comparison of acidification potential between ethanol blends and feedstocks.

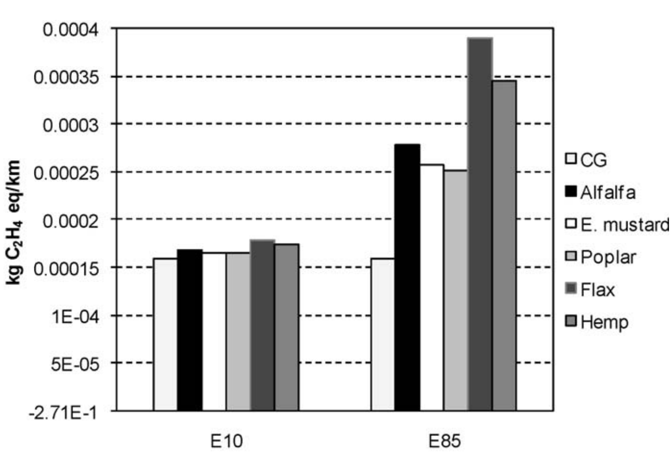

Fig. 4. Comparison of photochemical oxidants formation potential between ethanol blends and feedstocks.

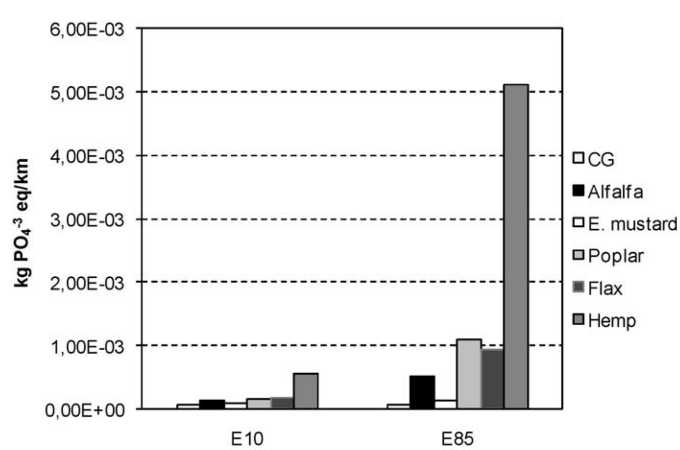

Fig. 6. Comparison of eutrophication potential between ethanol blends and feedstocks.

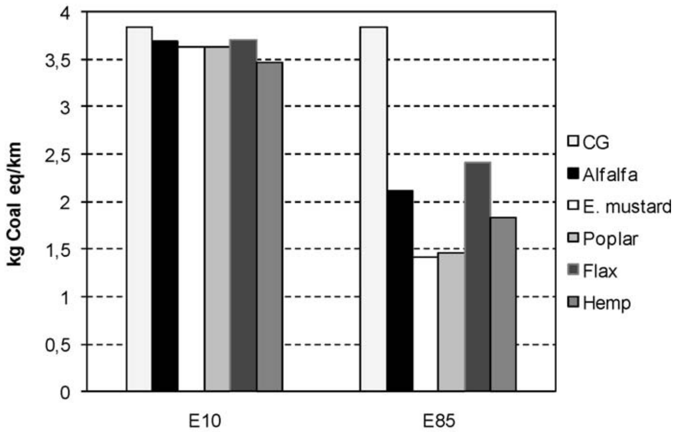

Fig. 7. Comparison of fossil fuels extraction between ethanol blends and feedstocks.

was to compare the environmental results obtained from the production and use of ethanol derived from five potential cellulosic biomass sources produced in Spain.

Several previous studies have presented ethanol-based fuels as interesting alternative to provide an opportunity to reduce GHG emissions as well as to increase energy supply [56]. However, the results significantly depend on the agricultural activities related with the biomass production as well as on the allocation procedure (allocation of emissions and resources used in the production of the products required when a process yields more than one products, common in agricultural processes). In the ethanol-based fuels life cycle, the agricultural activities related to the production of the feedstock have been identified as a key issue in impact categories such as acidification, eutrophication and global warming by different authors [7,20,25,26]. Hence, the weight of the allocation approaches of the agricultural products on the environmental results. The diversity of the allocation approaches has caused much debate among LCA practitioners and researchers [19,57]. Nguyen and Gheewala [26] analysed the influence of the economic allocation approach applied to the products obtained in the sugar milling since the molasses obtained in this step from the sugar cane are the feedstock in the ethanol plant. In line with this study, large differences where predicted as N_2O emissions since these emissions (mainly derived from N fertilization in agriculture subsystem) are one of the main responsible factors, which contribute to the increase of GHG emissions in ethanol-based fuels compared to gasoline.

In our study, allocation should not be necessary in two biomass crops, that is, poplar and Ethiopian mustard since they are the single product (corresponding allocation factor = 100%). However, in the remaining crops under comparison: alfalfa, flax and hemp, the avoidance of allocation is impossible since the production of stems, shives and hurds takes place together with leaves (alfalfa), seeds and fibres (flax) and dust and fibres (hemp). The higher the contributions from agricultural activities are, the most important the influence of the allocation factor. González-García et al. [21,31] applied both the economic and mass allocation in flax and hemp agricultural production, screening that smaller partitioning factors (achieved in economic allocation due to the lowest prices for flax shives and hemp hurds in the market in comparison with fibres) result on lowest contribution to the environmental profile and environmental credits in terms of PO, AC, EP and FF.

According to our results, the use of ethanol blends as transport fuel in a FFV can reduce the GHG emissions depending on the ratio of ethanol in the blend and the feedstock. Ethanol-based fuels production and use contributes to GHG emission; however, CO_2 is adsorbed back by the crops during growth. Therefore, in order to determine the net amount of CO_2 either being released or sequestrated, the assimilation rate of CO_2 for growth is considered. In this context, the use of Ethiopian mustard based ethanol in terms of GW show the best environmental results with reductions up to 145% (E85) in comparison with gasoline. The low intensive energy activities required per ha in this crop as well as the assignment of all CO_2 sequestrated to this biomass source, implying that using Ethiopian mustard as ethanol feedstock has superior qualities, acting as a carbon sink to reduce the amount of CO_2 in the atmosphere as compared to the remaining sources.

Concerning the results for impacts on PO, AC and EP, the contributions are higher when shifting from CG to ethanol blends due to influence from feedstock cultivation. Moreover, it can be seen that different fuel options show better performance in different categories. Concerning PO, although the combustion of ethanol-based fuels produce lower emissions of CO, there are higher emissions of acetaldehyde derived from ethanol production which considerably contribute to PO. As a result, contributions to PO from the blend use increase with the ratio of ethanol in the blend. Poplar seems to be the best option regardless the ratio of ethanol in the blend. This result is mainly due to the high annual biomass production per ha as well as the high ratio of ethanol production per feedstock (0.32 t ethanol/t of dried biomass). Therefore, the main responsible of these contributing emissions are the ethanol biorefinery and blend use. With regard to AC, Ethiopian mustard and flax are the best alternative when E85 and E10 are used as transport fuels. The levels of AP increase highly when the ratio of ethanol in the blend increase. This level is due to not only diffuse emissions from fertilizer application in agricultural activities but also, the acidifying emissions derived from diesel production (for agricultural machineries). These emissions are in fact, the main hot spot and the low intensive agricultural practices in both crops result on a lowest environmental profile in comparison with other feedstocks (Table 3).

Ethiopian mustard is also the best option in terms of eutrophying emissions regardless the ratio of ethanol in the blend. Nitrogen based emissions to air and water from the nitrogen fertilizers application are the main contributors to this impact category in all case studies and, although the allocation factor for this crop is the highest (100%), this crop shows a high biomass yield, which reduce the assignment of diffuse emissions per kg of feedstock. Regarding fossil fuels requirements, shifting from CG to ethanol blends always reduce their consumption. Higher reductions were highlighted in Ethiopian mustard and hemp hurds based ethanol for E85 and E10, respectively. These results are influenced by (i) lowest diesel requirement in agricultural activities and (ii) the lowest assignment factor of the agricultural activities to the hemp hurds (the allocation factor is 50%) respectively. As well, higher reductions are achieved for blends with higher amount of ethanol mainly due to the reduction of gasoline in the blend.

5. Conclusions

Using ethanol derived from lignocellulosic feedstocks as liquid fuel (E10 and E85 fuels) would reduce fossil fuels dependence and greenhouse gas emissions but would increase acidification, eutrophication and photochemical smog, compared to using gasoline as liquid fuel. For lignocellulosic ethanol from agricultural feedstocks to have guarantee, sufficient amounts of appropriate feedstock must be available as well as facilities to convert the feedstock to ethanol within a practical distance of the feedstock production area. Feedstock producers would have to be willing to produce energy crops and/or remove a portion of residues from their fields, would have to do so in a sustainable manner.

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